Chapter

12

Risk Management

FOREWORD: The Facility Manager's Perspective

Donald G. Eagling

Risk management is an important part of a comprehensive earthquake safety program. It is inherent in establishment of lateral force criteria for the design of buildings and equipment, including research facilities and operations. Building codes, such as the *Uniform Building Code* (UBC) (Ref. 1), establish *minimum* seismic requirements for life-safety and essentially provide protection against collapse. Damage control is not the prime objective. Many code provisions, such as limitations on story *drift* (deflection between successive stories based on prescribed lateral forces), have the effect of reducing damage, but the real earthquake will cause deflections much greater than *code deflections*. When damage control is an important consideration, design must account for these larger deflections. This protection is not inherent in the code. One approach is to analyze a structure with the objective of predicting or estimating the location and extent of damage that will probably result from a major earthquake. *In this way, additional attention to design detail can be applied specifically in the area of concern to "buy insurance" against damage for little extra cost; this is an example of good risk management.*

Liability is a legitimate concern in risk management. Often, however, this concern is translated into legalistic solutions, rather than practical solutions that do more to mitigate seismic hazards. For example, the code is generally not retroactive, so it is not legally incumbent upon the *responsible official* to upgrade an existing building to current standards. Furthermore, some earlier editions of the seismic code made it *legally* possible to design and construct hazardous buildings such as the Olive View Hospital, which was destroyed in the 1971 San Fernando, California earthquake or the apartment buildings destroyed in the 1994 Northridge, California, earthquake. Nonductile reinforced-concrete frame buildings such as the five-story Kaiser Permanente office building suffered partial collapse in the Northridge earthquake.

Presidential Executive Order 12941 (Ref. 2) adopted minimum standards for assessing the seismic safety of existing Federally owned and leased buildings and mitigating unacceptable risks in them. The Department of Energy (DOE) issued criteria for the evaluation, modification, or upgrade of existing facilities in DOE-STD-1020-94 (Ref. 3) which also covers new construction for natural phenomena hazards. In essence these new regulations, unlike the seismic provisions of the UBC, are retroactive.

A decision not to review an existing building because it was once designed to code is a legalistic solution to avoid liability, but it does nothing to mitigate seismic hazards that may exist. This legalistic position under the protective umbrella of the code is becoming more difficult to assume because the engineering profession is now much more aware of hazardous buildings that have been *built to code.* Also, in recent years, courts have made substantial monetary awards to occupants of poor buildings injured in earthquakes. One cannot be certain to avoid liability by remaining ignorant of hazards. The legal issue may well be whether or not such a building is commonly known by members of the profession to be hazardous.

The risk of liability should be managed carefully when structural hazards are revealed as a result of seismic safety surveys and reports. For example, if a building is reported to be a collapse hazard, the official responsible for the safety of the occupants should take steps to mitigate the hazard. It is important to seek funds actively to abate the hazard and to inform the occupants that the building is deficient. While these steps will not guarantee immunity, failure to take them certainly increases liability.

The problems of funding rehabilitation work are usually difficult, and achieving solutions is time consuming. The longer hazards continue to exist, the greater the risk of liability becomes.

A public agency cannot legally go out of business; therefore, it cannot spend its available funds so heavily for rehabilitation that it cannot fulfill its prescribed missions. This fact weighs against liability, but does not provide immunity. In the event that a damaging earthquake results in litigation, the pertinent issue is: what funds were available to responsible officials and what were they used for? With this in mind, one approach to managing the risk of liability is to take basic risk-reducing steps that can be identified immediately (assuming that the hazard cannot be easily abated in a short time), then follow due process to find a permanent solution to the problem. Examples of emergency steps are:

- adding temporary supports
- reinforcing structural joints
- installing epoxy grouting
- removing potential hazards
- changing or reducing the occupancy loading.

Normally, emergency funding can be found for such purposes while the more time-consuming tasks of evolving a permanent solution and developing adequate funding take place. *The important point is that responsible action (within constraints) must take place if liability is to be minimized.*

It is likely that a seismic safety survey will turn up a number of structurally deficient buildings and facilities. This is a common result when such reviews are carried out. For years, many buildings were designed with nonductile, reinforced-concrete frames which were then permitted by code, but are now known to have poor seismic resistance. Many older buildings have no formal or predictable lateral-force-resisting system. Sometimes building alterations have reduced or destroyed the resistance incorporated in the original design. The point is, a seismic safety survey will likely present the responsible official with a multiplicity of hazards and risks to manage.

It is important to mitigate the risks on the basis of priority, but it is even more important for life safety not to get bogged down in a complex series of studies or a methodology that slows the process of abatement. A simplistic priority system based on due process and responsible professional judgment is sufficient. As with the Richter scale for measuring the magnitude of earthquakes, it is not as important that the result is accurate as it is that relative size (or priority) is easily and quickly established.

The same selection principle should be applied when seismic safety surveys are initially carried out. That is, the priority system for the sequence in which buildings and facilities are surveyed should be simplistic and direct. Obvious problems, possible collapse hazards, and high-risk facilities, such as those with hazardous dispersible contents, should be reviewed early. High-occupancy buildings and lifeline facilities also should be early on the list. It is important that the survey is not held back by an academic approach to the multiplicity of potential hazards and the complexity of the problem. *The recommendation is to keep the approach simple, rely on good professional judgment, and move forward expeditiously.*

One stumbling block to seismic safety is the ever-present concern for accurately estimating the intensity of the potential earthquake that a given site might experience. For various political, academic, and psychological reasons, the immediate, basic need to find out whether a brace is indeed missing too often becomes secondary to guessing how big the earthquake is going to be. Commonly, the problems uncovered in a seismic survey have less to do with lateral force criteria to be applied than with obvious or simple design deficiencies such as missing links, brittle members or connections, lack of continuity, or just poor construction. When a building or facility is found deficient, the size of potential seismic input is only one of the considerations that may be brought to bear on corrective measures. Usually there is ample time to develop detailed lateral force criteria after the real problems are revealed. Often design criteria for strengthening an existing building are more dependent on the deficiency to be corrected than on seismic input.

The recommendation is: don't delay the seismic survey in order to study the potential seismicity of the site. Experience shows that this approach is not good risk management.

The design criteria for new buildings are rather well established in building codes, but this is not true for rehabilitation work. Here good risk management requires more careful consideration. The lateral force provisions in the code provide good guidelines for rehabilitation design, but often, lateral force resistance is only part of the problem. As discussed, brittleness, lack of continuity or redundancy, deflections, poor detailing, poor workmanship, and many other possible deficiencies may exist. From the standpoint of risk management, it is even more important than in the design of new facilities that the designers of rehabilitation work give particular attention to seismic structural diagnosis and criteria development.

Once it is determined that a building has a serious structural deficiency that must be corrected, another kind of problem is often present. The building may have other code deficiencies by current standards that are not central to the main hazard. That is, the main structural deficiency may be a collapse hazard, but the other code deficiencies may not present life-safety hazards. The question may then arise: will responsible officials (or the engineers who design the rehabilitation work) be placed in a position of liability if the design does not correct all of the deficiencies by current code standards? Often it is not economically feasible or even good risk management to correct everything. For example, funding may be better used to correct two collapse hazards rather than spend it all on one building to bring everything up to code.

The recommendation is to achieve the most life safety for the funding available, but mitigate possible liabilities for the design professional by careful due process. For example: a criteria board can be established consisting of professionally knowledgeable members such as the responsible rehabilitation designers, the plan checker (preferably an independent consultant), and the Building Official (the in-house person responsible for enforcing the code for design and construction).

The authority to set seismic criteria, not covered by the UBC (Ref. 1) or DOE-STD-1020 (Ref. 2), should then be officially delegated to this *expert* group. Often detailed criteria needed for seismic retrofit will not be available from building codes or regulations. Also, it may not be practical or possible to rid an existing building of non-conforming materials that are not life threatening from earthquake hazards.

Court judgments have held that the responsible authorities are immune from liability for acting in a discretionary manner if they have the legal authority and expert knowledge to do so. The authority must be properly delegated, and *knowledge* implies professional judgment in the practice involved. The engineer in responsible charge of the retrofit design will be reasonably protected by the due process involved, assuming that he or she fulfills his or her design-responsibilities satisfactorily.

California engineers generally believe the buildings they design will be subjected to a damaging earthquake during the lifetime of the structure. They do not consider the hazard to be one that in all likelihood will not occur. They are also aware that the earthquake is the real *master inspector.* If there is a gap in the lateral-force-resisting system, the consequences will be more serious than statistical. This point of view has a very positive effect upon risk management as applied to design. As an aside, it is interesting to note that the probability estimated for a magnitude 7 earthquake in the San Francisco Bay area is now based on the 30-year period commonly used for home mortgages.

In areas of the country where earthquakes are very rare events, it is difficult for engineers to take them seriously, particularly in the design of conventional structures. It is a fact that extremely few buildings in the midwest and east have been designed for earthquake safety, even in those areas where it is well known that damaging earthquakes have occurred in the historical past. Many buildings are constructed of unreinforced unit masonry, one of the building types particularly susceptible to earthquake damage and collapse. A great deal of progress could be made by simply avoiding the use of unreinforced unit masonry in new construction.

In *earthquake country,* the choice of criteria for seismic design can be a relatively simple matter, if one believes that the great earthquake is imminent. In this case, the design earthquake can be taken relatively close to the maximum expected earthquake. This might correspond to 0.2g base shear using the static lateral force design approach or to 0.8g using ground spectra acceleration for dynamic analysis. This design approach is based on what is known as the *minimax decision,* because it minimizes the maximum losses in the future.

In areas of the country where the potential for a great earthquake exists but the probability is extremely low, the choice of criteria may be more difficult. The maximum expected earthquake is not a practical choice for the design of most conventional structures in such areas. A *more fundamental consideration relates to the decision of whether or not to design for seismic forces at all. However, considerable seismic resistance can be achieved for very little extra cost by simply applying the principles of static lateral force design and making sure that the system is continuous and ductile.* The insurance available in such a minimal approach is a true bargain in risk management. The lateral force factor to be used is of secondary importance. However, if the building code values are used, one has some assurance that this choice is properly coordinated with its other provisions.

Risk management deals primarily with a variety of nontechnical issues that must be carefully managed in a comprehensive earthquake safety program. The intent of this discussion is to provide facility managers with practical guidance through the maze of socio-political, legal, and economic risks that may impede the progress and success of such a program.

High on the list of effective risk-management techniques related to seismic safety is the so-called *third-party plan check* that is described elsewhere in this book. This independent plan check, together with proper field inspection of construction (whether new or rehabilitation work), is highly recommended as one of the best ways of ensuring seismic safety in structural design and construction. This important topic is discussed in detail in Chapter 12a, *Quality Assurance by Peer Review*.

In Chapter 12b, *Risk Management Analysis*, both practical and technical issues of risk management are discussed, providing techniques for dealing with the probabilistic nature of earthquakes and illustrating methods of relating hazards, mitigation costs, and probability to management decisions. Included are examples of the decision-tree analysis technique for diagramming and tracking the risk management decision process, forecasting rare events, and dealing with multiple hazards.

References

1. *Uniform Building Code,* International Conference of Building Officials, Whittier, California, 1994.

2. *Seismic Safety of Existing Federally Owned or Leased Buildings,* Presidential Executive Order 12941, Washington, D.C., December 1, 1994.

3. *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities,* DOE-STD-1020-94, Washington D.C., April 1994.

Chapter

12a

Quality Assurance by Peer Review

Frank E. McClure

Introduction

DOE Order 5700.6C (Ref. 1), *Quality Assurance,* (QA) requires that design and construction of DOE facilities incorporate the necessary review requirements to ensure that established program quality assurance objectives are met in the design per se, construction contract documents, and actual construction. *Project Peer Review* (PPR) is one of the best ways to ensure that a structure can resist earthquakes.

The American Consulting Engineers Council (ACEC) and *American Society of Civil Engineers* (ASCE) have undertaken a very significant program to improve the quality of constructed projects. Their joint publication, *Project Peer Review Guidelines: 1990,* (Ref. 2) is an excellent reference for persons involved in PPR. It is intended to help implement the concepts presented in the ASCE *Manual of Professional Practice*, Number 73, *Quality in the Constructed Project*, 1990, Chapter 13, *Peer Review*.

The PPR process is intended to enhance the quality of a constructed project by providing an external review of design assumptions, project management, and final design documents. However, responsibility for the structural design remains with the design organization's *Engineer of Record* (EOR). The written agreement implementing the peer review should state this unambiguously.

PPR is an autonomous and objective review of a proposed project by qualified engineers who hold neither a personal interest or claim in the project, nor any conflicts of interest. The reviewer should be in no way beholden to the commissioning agency, hereafter referred to as the *client*, who engages and pays them, nor to the EOR.

PPR is a documented, critical review performed by peers who are independent of those who performed the work, but who have technical expertise and experience in similar projects at least equivalent to those who performed the original work. PPRs can vary in scope from just reviewing the general design criteria to making an in-depth, critical review and evaluation of design criteria, design, and construction contract documents. An in-depth review requires interpretation and mature judgment in addition to normal technical reviews for compliance with DOE Orders and Standards. The *peer review* has a specific purpose, scope, format, and duration, which should be documented and agreed to by all parties.

The purpose of PPRs is to ensure proper designs and procedures, evaluate new or especially innovative designs, and improve project quality. PPRs are not organizational, management, *constructability*, or *value-engineering* reviews.

Review Requirements in DOE Order 6430.1A

DOE Order 6430.1A, *General Design Criteria*, (Ref. 3) requires that facility designs incorporate the necessary QA provisions to ensure that established program and project objectives are satisfied. The assurance that project construction documents (drawings and specifications) conform to project design codes and standards is critically important in satisfying those objectives.

For buildings and other structures designed to resist earthquake forces, Order 6430.1A requires that an independent or peer review of the seismic design be made for facilities and buildings where a seismic event would risk life-safety or large economic loss. Reviews are required at two stages; the first at the end of preliminary design (Title I, preliminary drawings and specifications) and the second just before the final design (Title II, final working drawings and specifications) is complete. An additional review at 50% completion of Title II documents also is recommended. It is intended that this additional review preclude early incorporation of errors and/or omissions so that later in the final design process the EOR will not be reluctant to make the changes necessary to correct them.

DOE Order 6430.1A has QA requirements related to review of structural design calculations and construction documents (drawings and specifications). Specifically, Section 0140, *Quality Assurance*, requires that an adequate QA program provide four assurances:

- The design will satisfy program and project requirements
- That prepared drawings and construction specifications adequately address QA requirements
- Construction can be performed in accordance with the design
- Tests confirm the adequacy of the design and the quality of construction and manufactured components, where appropriate.

The Order also requires that provisions be made for review and checking of design calculations, drawings, and construction specifications by qualified personnel other than those responsible for the original design. To the extent practicable, and particularly in the case of innovative designs, designs must be reviewed by consultants competent in construction or manufacturing techniques to confirm practicability of construction or manufacture.

The QA requirements in DOE Order 6430.1A take on the aspects of *plan-checking* as discussed in the *Uniform Building Code* (UBC) and go beyond the usual scope of work for PPRs, as discussed previously.

Review Requirements in DOE STD-1020

DOE-STD-1020, *Natural Phenomena Hazards Design and Evaluation Criteria for DOE Facilities* (Ref. 4) which implements DOE Order 5480.28, requires that designers use special QA procedures and that their work be subject to independent peer review for facilities in *Performance Categories* PC-2 and above.

To achieve well-designed and constructed earthquake-resistant facilities or to evaluate the seismic vulnerability of existing facilities, it is necessary for designers to:

- Understand the seismic response of the facility
- Select and provide an appropriate structural system
- Provide seismic design detailing that allows tough ductile response and avoids premature failures caused by instability or low-ductility response
- Provide a material testing and construction inspection program that ensures that construction complies with the intentions of designers.

All DOE *structures, systems, and components* (SSCs) must be designed or evaluated using an earthquake engineering QA plan as required by DOE Order 5700.6C and DOE STD-1020. The level of rigor in such a plan should be consistent with designated performance categories and their performance goals.

For Performance Categories 1, 2, 3, and 4, QA plans should include a statement (on the design drawings) by the EOR explaining the earthquake design basis including:

- Description of the lateral-force-resisting system

- Definition of the earthquake loading used for design or evaluation.

Seismic design or evaluation calculations should be checked for numerical accuracy and for theory and assumptions. The calculations must be signed by the responsible engineer (EOR) who prepared the calculations, the engineers who checked numerical accuracy, and the engineers who checked the theory and assumptions.

For new construction, the EOR should specify a material testing and construction inspection program. In addition, design engineers should review all testing and inspection reports and periodically make site visits to observe compliance with plans and specifications. For certain circumstances, such as the placement of reinforcing steel and concrete for special ductile frame construction and welding steel moment-resisting joints, the EOR should arrange to provide a specially qualified inspector to continually inspect the construction and to certify compliance with design and specifications.

For Performance Categories 2, 3, and 4, DOE-STD-1020 requires that all aspects of the seismic design and evaluation include independent peer review. The seismic design or evaluation should include design philosophy, structural system, construction materials, design/ evaluation criteria used, and other factors pertinent to the seismic capacity of the facility.

The review need not provide a detailed check, but rather identify oversights, errors, conceptual deficiencies, and other potential problems that might affect facility performance during an earthquake.

The peer review is to be performed by independent, qualified personnel. Peer reviewers must not have been involved in the original design or evaluation. If they are from the same company or organization as the designer/ evaluator, they must not be part of the same project (or program) or be influenced by cost and schedule considerations. Individuals performing peer reviews must be licensed civil or mechanical engineers with five or more years of experience in seismic evaluations. It is very beneficial to have peer reviewers participate early in the project, such as the start of preliminary design so that rework can be minimized.

Peer Review at Lawrence Berkeley Laboratory

In the aftermath of the destructive 1971 San Fernando earthquake in southern California, the Facilities Engineering Department of the University of California's Lawrence Berkeley Laboratory (LBL) implemented an independent seismic design review procedure long before there were DOE PPR requirements. The stimulus for this independent seismic design review policy resulted from a 1971 seismic vulnerability study that showed that many buildings were not properly designed to resist earthquakes even though the University of California required designers to follow the seismic provisions of the UBC in effect at the time of construction.

The use of independent seismic review has proved to be prudent risk management as exemplified by the successful earthquake performance of public schools in California that had been constructed and approved under the procedures of the *California Field Act*. The Field Act requires, among other quality assurance procedures, an independent *plan check* of the structural design calculations and the construction documents by the Division of the State Architect.

At LBL, independent structural and seismic design reviews are made by consultants experienced in seismic design and evaluation of buildings and in field investigations of earthquake damage to buildings. These reviews are usually made in three stages for facilities having potential risk to life safety, facilities using hazardous materials, and facilities with a potentially large economic loss.

The first review is made at the end of preliminary design, or Title I, services. The second review is made at 50% completion of Title II construction documents and design calculations. The third review is made when the final design (Title II construction documents and design calculations) are about 95% complete, before bids are taken, so that resolution of the final comments can be incorporated in final bid documents. At the completion of the reviews, when comments and questions are resolved, the review engineer submits a simple report recording that the design and construction documents meet the intent of the project program and design criteria.

Structural and seismic design reviews cover design philosophy, criteria, framing systems, construction materials, and other factors pertinent to the seismic capability of the proposed facility. *Particularly important is the check for continuous load paths and the adequacy of their strength, stiffness, and ductility to transfer the seismic forces from the points of origin and application to the final points of resistance.*

In summary, peer review by an independent consultant or peer group need not provide a detailed check of the spacing of the reinforcing steel or numerical accuracy of design structural calculations. Rather, it is a review to identify oversights, errors, conceptual deficiencies, and other elements likely to cause problems during construction, after the building is completed, and during earthquakes. Peer reviews catch costly design mistakes in judgment, design criteria, and philosophy. This has been true at LBL for many projects, large and small, since 1971. For major facilities, an independent peer review can more than pay for itself by uncovering design deficiencies before bids are taken and construction starts.

Problem Areas With Project Peer Review

The potential liability of the peer reviewer is one of the first questions asked by all parties to the peer review process. Professional engineering societies adhere to the principle that responsibility for the design/evaluation must remain with the design organization's EOR. This is in keeping with laws regulating the licensing of engineers. Consequently, they strongly recommend that written agreements outlining the scope of the peer review and the roles and responsibilities of all parties be entered into prior to the start of peer review work. They have proposed sample contract indemnification clauses for the inclusion in the written agreement to limit the liability of peer reviewers.

The fact that the EOR's work will be subjected to the peer review process should be incorporated in the *request for proposal* (RFP) as part of the *Architect/Engineer* selection process. This is essential if the client is to avoid cost extras for work associated with peer review.

The ACEC has prepared several manuals covering peer review to guide clients (who authorize and pay for peer reviews), EORs, and peer reviewers in developing written agreements specifying the scope of review work and responsibilities of the parties to the review.

Unless a written agreement is executed defining the responsibilities of all the parties, clients may believe that peer reviewers are offering a *Good Housekeeping Seal of Approval* and accepting co-responsibility for the design with the EOR when they agree to review the project seismic design. If an adverse situation should arise, clients may attempt to hold both the EOR and the independent peer reviewer liable.

There is little legal history on the liability of the peer reviewers. However, it is reasonable to assume that in this litigious society, it is difficult to be truly free from liability. Reviewers should use prudence and good judgment, conduct their review appropriately, and keep good documentation.

There can be some *human problems* with the selection of independent peer reviewers, how the peer review process is handled, and the attitude and conduct of clients, EORs, and peer reviewers.

Clients should avoid engaging PRs who are too closely linked personally with the EOR through long-time personal relationships, participating in joint ventures, or working together on professional committees. There may be a reluctance to criticize a friend's design or point out omissions if there have been prior close personal relationships. These types of relationships preclude truly independent judgments by PRs.

Also, clients should avoid interchanging the roles of EORs and PRs on projects. This tends to encourage less rigorous peer review because PRs on a current project realize that EORs might become PRs on their future projects.

The review should be started early in the design process. Significant design errors or omissions discovered at completion of the construction drawings and specifications are often difficult and costly to correct. Consequently, EORs may defensively try to justify errors or omissions that, if found earlier, could have been easily corrected.

An unfortunate situation could arise in which PRs and EORs disagree, and EORs refuse to make the changes suggested by PRs. Clients can be left in the unenviable position of trying to sort out which one is correct or try to force a compromise. In such cases, clients may be forced to engage another third-party reviewer to help them resolve the dispute. This situation can result in delays in meeting project deadlines, additional review costs, and increased costs for inflation. Every DOE site should have one qualified person who is delegated responsibility for enforcing the building code. This person, usually designated as the *Building Official* for the site, has the authority to resolve such issues. It is most important, however, that the EOR not be required to reduce safety factors as a result of peer review. This could negate the EOR's professional responsibility for the design. Under no circumstances should a PR supplant the original EOR whose work the PR has reviewed.

Potential *conflicts of interest* can arise. It is recognized that PRs should not take commissions to perform detailed *plan-checking* reviews on projects for which they were the project peer reviewers. Clients should be aware that PRs could unconsciously use the peer review process to diminish the professional reputation of a fellow competitor when they aggressively look for everything wrong with the EOR's design. Sometimes a PR attempts to show up the EOR by finding as many errors and omissions as possible in the EOR's design to show the EOR that the PR is a better engineer.

Generally, LBL has had no significant problems in any of these areas over the 25 years that independent plan checks have been used there. On the other hand, significant deficiencies have been corrected or the design has been significantly improved in over 90% of the projects reviewed. Plan checking fees have been nominal, usually less than 0.2% of construction cost.

The peer review should be a *friendly* review of a fellow design professional's work. The review is initially aimed at making every effort to ensure that serious errors and omissions are found and corrected. It should not be a *nit-picking* type of review.

References

1. DOE Order 5700.6C *Quality Assurance*, U.S. Department of Energy, Washington, D.C., 1991.

2. *Project Peer Review Guidelines*, American Consulting Engineers Council/American Society of Civil Engineers, New York, New York, 1990.

3. DOE Order 6430.1A, *General Design Criteria*, U.S. Department of Energy, Washington, D.C., 1989.

4. DOE-STD-1020-94, *Natural Phenomena Hazards Design and Evaluation Criteria for DOE Facilities*, U.S. Department of Energy, Washington, D.C., 1994.

Chapter

12b

Risk Management Analysis

Jack R. Benjamin

Introduction

Risk management from the technical point of view is the formal process by which hazards are mitigated under the constraint that all acceptable mitigation measures cannot be accomplished instantaneously. In the simplest case, risk management may determine that an acceptable mitigation measure involves only following a check list to ensure that an important item in operation or maintenance is not forgotten. At the other extreme, there are important facilities that may be of questionable structural integrity—yet are subject to diverse human and natural hazards—and for which resources for hazard mitigation are not only limited but become available as a function of time. The problem in this latter case is that of obtaining the best allocation and expenditure of scarce resources at each instant of time.

Major technical concerns in risk management of important facilities include the uncertainties inherent in the hazards and effectiveness of any mitigation effort. It is common for hazards to be described in probabilistic terms by level and occurrence over a period of time. For example, the earthquake hazard may be described by an effective peak acceleration level that has a 10% probability of being exceeded in 50 years, or a wind hazard may be described in terms of a velocity with a return period of 100 years. In contrast, the effectiveness of any mitigation effort is traditionally described in deterministic terms. For example, the structure designed to the code should not collapse even under severe earthquake load and should sustain only minor structural damage during moderate ground shaking. These estimates of behavior are deterministic, because there is no estimate of the probability of different damage levels. Risk management, therefore, requires combining diverse types of forecasts, both deterministic and probabilistic.

The Decision Tree

The decision tree provides a useful device for diagramming and systematically keeping track of risk management decisions. The tree is the framework for evaluating alternative mitigation plans and, because the tree can be updated, it can continuously model the decision situation as a function of time.

A simple decision tree for two earthquake-related hazards is shown in Fig. 12b-1. Assume that the responsible official or panel of professionals is to decide on the risk management program. This *decision maker* is considered to be at Apex 1. With an available $100,000 expenditure, it is further assumed that only two different mitigation plans are acceptable. With Action A, all resources go to major structural

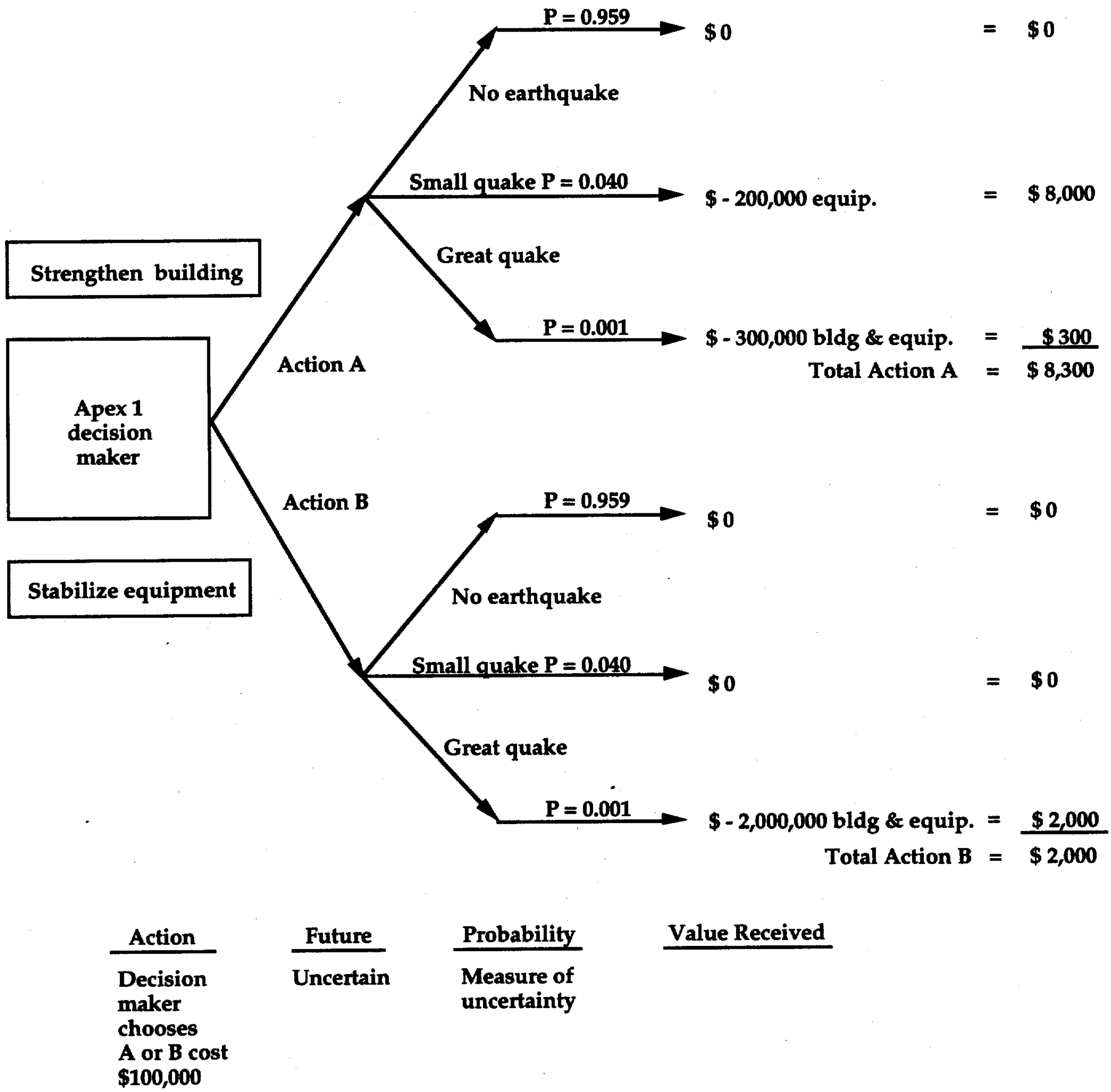


Fig. 12b-1. Risk management decision tree.

strengthening of the building, while with Action B all resources go to stabilizing critical equipment in the building. The equipment can be severely damaged by a low-level earthquake that the building survives. If the earthquake ground motion is very severe, the building structural system fails and the building collapses, destroying the critical equipment, even if it is stabilized. The earthquake that could cause the building to fail is a very rare event, while low-level earthquake ground motions frequently occur.

Now, if decision makers take Action A to strengthen the building and the future (one year) includes the small earthquake, the equipment loss is shown to be $200,000. Similarly, if Action A is taken and there is a great earthquake, the total loss is $300,000, consisting of partial-building and complete-equipment damage. If no earthquake occurs, there is no loss or gain except that the $100,000 expenditure is a sunk cost.* In contrast, if the available funds are expended to stabilize the equipment (Action B), there is no loss with a small event, but a $2,000,000 loss (total loss of building and equipment) is estimated to be the consequence of very severe ground motion from a great earthquake.

Thus, the decision tree contains the consequence of taking an action and finding the future. The probabilities of occurrence of the hazard are noted on the tree so that the diagram contains all of the basic ingredients for the decision. The units of the consequence may be dollars or any other convenient and consistent measure of preference.

For simplicity, the *decision maker* in Fig. 12b-1 must choose either A or B. Action B reduces the possible loss from the occurrence of a frequent but small earthquake, while Action A reduces the worst possible loss from a great event. The optimum action, A or B, depends on the probabilities of occurrence of earthquake levels in any one year in the life of the facility. Two contrasting viewpoints exist in choosing Action A or B. First, if the $2,000,000 loss with a great earthquake is so large as to be completely unacceptable, the optimum action is A. This type of decision is called a *minimax decision* because it minimizes the maximum possible loss that can be experienced in the future. *This type of decision rule fits the case in which one of the possible losses is not acceptable, or the probability of occurrence of the level of hazard does not effectively influence the decision.*

In contrast, if the losses shown are severe but not catastrophic, the optimum decision can be determined by weighting the losses by the probabilities of occurrence and summing for each action. The optimum decision is then the one with the smallest weighted loss. This is known as the *expected-value* decision rule. Using this decision rule, the expected loss per year with Action A is 0.040 x $200,000 = $8,000 for the small earthquake and 0.001 x $300,000 = $300 for the great earthquake. The sum is thus $8,300 per year. With Action B, the expected loss is $2,000 per year, so that the optimum action is to stabilize the equipment and accept the small risk that the entire building with equipment could be a total loss in a great earthquake.

In most practical problems, a combination of the minimax and expected-value rules is employed. For example, if a third Action, C, is also possible with intermediate loss characteristics, the minimax rule could be used to eliminate Action B, and then the expected value rule used to choose between Actions A and C. The choice of decision rules is obviously at the discretion of the "decision maker."

Forecasting Rare Events

The most common frequency statistic employed with rare events is the return period, T. The return period is the average long-run time between events of the same description. That is, if the return period of the 1906 San Francisco earthquake is 200 years, over a million or so years, on the average, one such earthquake occurs each 200 years. The actual record would show considerable variability in the time between events, but the average time between events is 200 years. This does not mean that the next event is forecast for 1906 + 200 = 2106.

If the return period is 200 years and the event is equally likely to occur any year, the probability of occurrence in any one year is approximately $1/T = 1/200 = 0.005$. If the probability of occurrence in any one year is 0.005, the probability of nonoccurrence is obviously 1 - 0.005 = 0.995. The probability of nonoccurrence in any two years is then 0.995 x 0.995 = 0.990. Thus, the probability of at least one occurrence in these same two years is 1 - 0.990 = 0.010. The probability of nonoccurrence in 200 years of the 200-year event is $(0.995)^{200} = 0.37$, so that the probability of at least one occurrence is 1 - 0.37 = 0.63. Thus, the probability of occurrence of an event with a return period of T years in a time span of T years is approximately two-thirds.

The results of calculations of this type are given in Table 12b-1, in which return periods are related to the probability of occurrence in a given

*Note that to compare Actions A and B with the "do nothing" Action, in which the $100,000 expenditure is not made, requires that a future longer than one year be considered. It is assumed in this example that in the long run both Actions A and B are preferable to the "do-nothing" Action.

Table 12b-1. Return period data.

	Return Period in Years, T						
	10	20	50	100	200	500	1000
Approximate Annual Probability of Occurrence, p	0.1	0.05	0.02	0.01	0.005	0.002	0.001
Probability of Occurrence in T years	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Number of Years, n, for which there is a 10% probability that the T Year event will be exceeded (90% probability of nonexceedance)	1	2	5	10*	21	53	105
Number of Years, n, for which there is a 20% probability that the T Year event will be exceeded (80% probability of nonexceedance)	2	4	11	22	45	111	223
Number of Years, n, for which there is a 50% probability that the T Year event will be exceeded (50% probability of nonexceedance)	7	14	34	69	138	346	693

Equation: Probability of Exceedance $= 1 - (1-p)^n$

$$n = \frac{\log(\text{Probability of Nonexceedance})}{\log(1-p)}$$

Note: The event with a return period of 475 years has a probability of exceedance of 10% (nonexceedance of 90%) in 50 years.

*As an example, the probability is 90% that the largest event in 10 years will not exceed that with a return period of 100 years or probability is 90% for T = 100 years event will be satisfactory for 10 years.

time span, nonoccurrence in the same time span, and the probability that the largest event in a given time span will be the event with a return period of T years. The latter follows directly by defining the T-year event as the largest event of interest.

These same basic procedures for calculating occurrence probabilities apply to fires, high winds, accidents of all types including automobiles, and all other rare events that can only be classed and counted in a time reference.

Multiple Earthquake Hazards

One of the more common combinations of hazard events is that of earthquake followed by fire. It is not satisfactory, however, to assume that fire is certain after a major earthquake, because historical evidence shows that this combination, although more common than other combinations of events, is relatively rare. The actuarial data on the occurrence of fires do not apply to fires associated with earthquakes, because the latter are either too rare to materially influence the statistics or simply not treated as a separate class. However, a good physical knowledge of a facility aids in subjectively estimating the fire hazard related to earthquakes.

The simplest way to analyze possible multiple-hazard events is to use an event tree, which is the subset of the decision tree dealing with the uncertain future. An example of an event tree of the occurrence of fire and earthquake is shown in Fig. 12b-2. Beginning at the left apex and moving to the right, the branching shows the sequence of events that are possible in the time period of interest.

For the example of fire and earthquake hazards, the possible events are:*

- No fire and no earthquake
- Fire without earthquake
- Earthquake with subsequent fire
- Earthquake without subsequent fire.

*Note that it is possible to have a fire occur at one time and an earthquake occur at a different time during the same year. However, the probability of this type of multiple hazard actually occurring is assumed to be so small that it can be neglected in this analysis.

Because fires and earthquakes are rare events, the most likely probability is that of no earthquake and no fire. Assuming that the fire of concern, without earthquake, occurs on an average of one time a year per 1,000 laboratory buildings, the probability of occurrence in any given year is 0.001 for a specific laboratory building. If the earthquake of concern is the 100-year event, the probability of occurrence in a given year is 0.01. If there is an earthquake, it is subjectively estimated by a knowledgeable professional that the probability of a subsequent fire is 0.2. Thus, the probability of earthquake and subsequent fire is then 0.01 x 0.2 = 0.002 so that the probability of earthquake and no subsequent fire is 0.008 (i.e., 0.01 x 0.8).

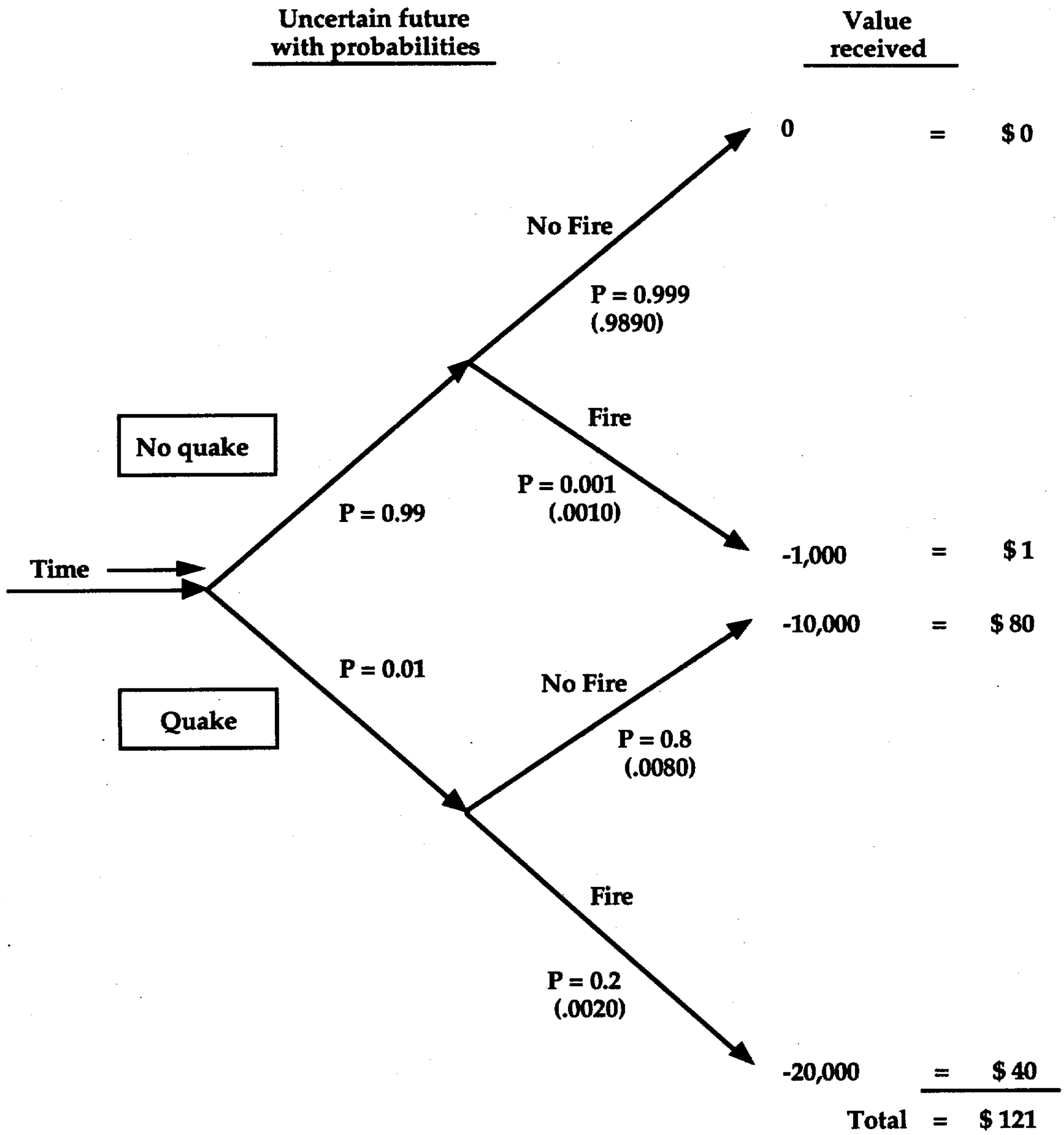
Assuming that losses associated with each event are estimated by analysis or judgment, the annual expected loss of earthquake and fire can be calculated. For example, if the loss caused by fire without earthquake is $ 1,000, the loss caused by earthquake without fire is $10,000, and the loss caused by earthquake with fire is $20,000, the total expected annual exposure for consideration in the mitigation plan (or for purchase of insurance) is:

Fire (no earthquake)	0.001 x 0.99 x 1,000	=	$ 1
Earthquake, no subsequent fire	0.008 x 10,000	=	80
Earthquake, subsequent fire	0.002 x 20,000	=	40
	Total annual exposure per building		$121

It is important to note that this weighting procedure assumes that the loss levels are within normal operational bounds and are acceptable. That is, if earthquake plus fire would result in total destruction (an abnormal and unacceptable outcome to some decision makers), while fire or earthquake by themselves do not eliminate long-range functional survival, the mitigation plan should take steps to prevent the possible losses resulting from total destruction.

Example of Analytical Risk Management

As an example of multiple-hazard risk management, assume that a risk management program is developed for a laboratory complex consisting of three buildings.



Total expected annual exposure from earthquake = $121

Fig. 12b-2. Event tree for fire and earthquake hazards.

Building A is an old masonry warehouse used to store laboratory supplies and spare equipment. It is likely to sustain total collapse in a major earthquake and moderate to total damage in a moderate earthquake. There is no fire hazard, unless the usage changes.

Building B is a modern one-story steel-frame structure housing very fragile laboratory equipment. Human occupancy is low level, but the fire hazard is high. There is a sprinkler system to prevent fire damage. In a major earthquake, the structure will sustain light damage with light to severe equipment damage. A fire is certain to start; however, the sprinkler system was not originally designed to displace the same amount without breaking as was the building. Thus, it is estimated that the chance of the sprinkler system working following a major earthquake is only 25%. If the sprinklers do not work, then the equipment will be further damaged and the chance of building collapse is 50%. In a moderate earthquake, the types of hazards are similar to those in a major earthquake; however, the extent of possible damage is less, and the estimated probabilities of the possible damage states are different. For example, the probability of the sprinklers' functioning is estimated to be 50% (this probability could be increased if periodic maintenance were performed). If the sprinklers *do not work*, the chance of building collapse is estimated to be 20% because it is more likely that the fire department will be able to control the fire before collapse.

Building C is a two-story unreinforced concrete-block masonry structure with timber framing. It is used for offices and has a high level of human occupancy. The building has no sprinklers, but has a moderate fire hazard, caused by a gas leak or inadvertent trash fire, etc. In a major earthquake, there would be moderate to heavy structural damage, but collapses would be localized because of the many closely spaced partitions. If a fire should follow the earthquake after a break in a gas line, there would be time for evacuation with minimum human injury, but further structural damage to the point of total loss would very likely occur. During a moderate earthquake, structural damage would be light to moderate. The chance of fire following the earthquake is much less; however, the consequences could be either heavy or total structural damage. If a fire starts in *Building C* without an earthquake, the possible damage levels range from light to total depending on the arrival time of the fire department.

The return period of major earthquakes at the site is estimated at 200 years, while for moderate earthquakes it is 20 years. It is further estimated that a fire level causing damage to *Building B* occurs on an average of one time a year per 50 laboratory buildings of this type, and important fire losses in office buildings such as *Building C* have a return period of 100 years. The other conditional fire probabilities are estimated by responsible professionals either subjectively or by analysis. Costs of the different possible damage levels to the three buildings and their contents are listed in Table 12b-2.

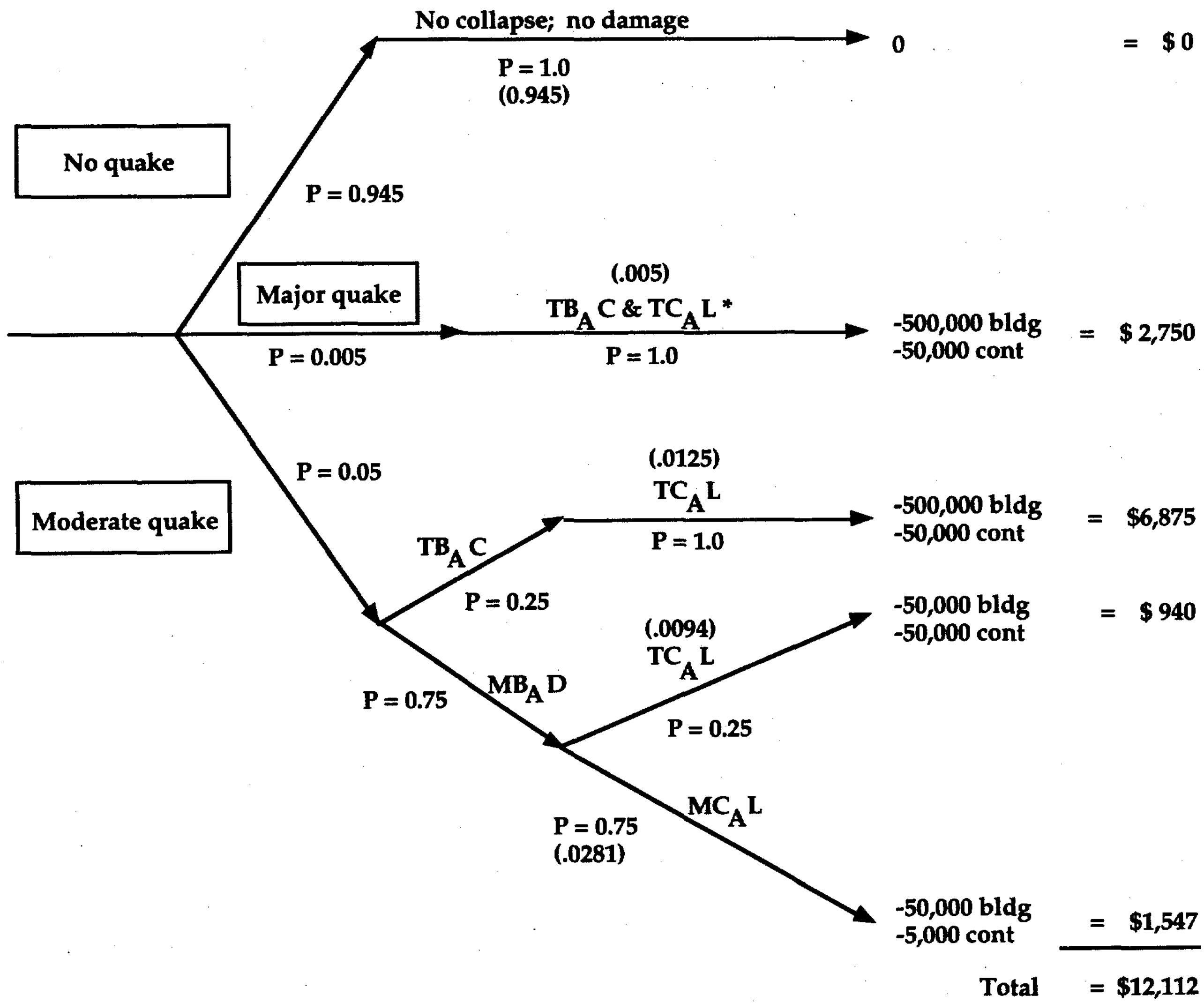
The first step in setting up the decision tree for the risk management program is to construct the event trees for each of the three buildings, realizing that these event trees will ultimately be merged to combine the hazard effects and consequences for all three buildings. Figs. 12b-3, 12b-4, and 12b-5 show the event trees for each building, respectively, along with the estimated costs of damage and estimated probabilities for each possible event.

Table 12b-2. Estimated costs of possible damage levels.

Building A		
Total Building A collapse (TB_AC)	=	—$500,000
Moderate Building A damage (MB_AD)	=	—$50,000
Total content loss (TC_AL)	=	—$50,000
Moderate content loss (MC_AL)	=	—$5,000
Building B		
Total Building B collapse (TB_BC)	=	—$1,000,000
Light Building B damage (LB_BD)	=	—$10,000
Severe equipment damage (SE_BD)	=	—$1,000,000
Moderate equipment damage (ME_BD)	=	—$100,000
Light equipment damage (LE_BD)	=	—$5,000
Building C		
Total Building C damage (TB_CD)	=	—$750,000
Moderate Building C damage (MB_CD)	=	—$200,000
Light Building C damage (LB_CD)	=	—$20,000
Lawsuits for injuries	=	—$1,000,000

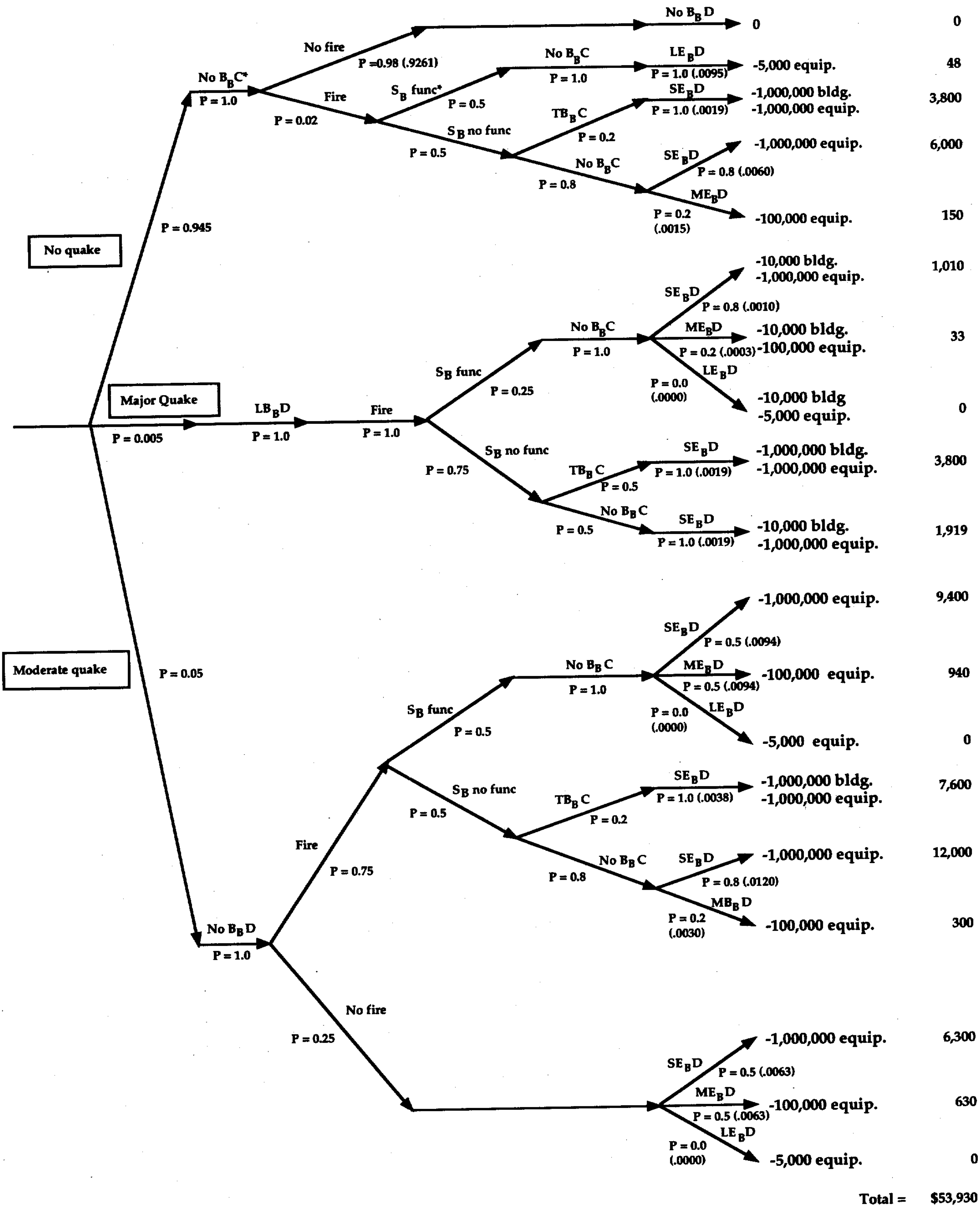
Multiplying the estimated loss for each possible event branch by the probabilities along that branch and summing the products gives the expected annual loss for each building. These expected annual exposures are the basis for determining the cost-effectiveness of different mitigation alternatives.

For example, considering no mitigation effort, the expected annual exposure for *Building B* from fire and earthquake hazards is $53,900. By providing a more aggressive maintenance and repair program for the sprinkler system in the building, the probabilities that the sprinkler system will function are increased to 80% for a fire following a moderate earthquake and 50% for a fire following a major earthquake. The probability that the sprinklers will function in a fire without an earthquake is also increased to 80%. The expected annual exposure with the improved maintenance and repair is thus $41,200, which is an expected annual savings of $12,700. If the annual cost of this maintenance and repair program is more than $12,700, then the mitigation is not cost-effective.



Expected annual exposure from earthquake = $ 12,100

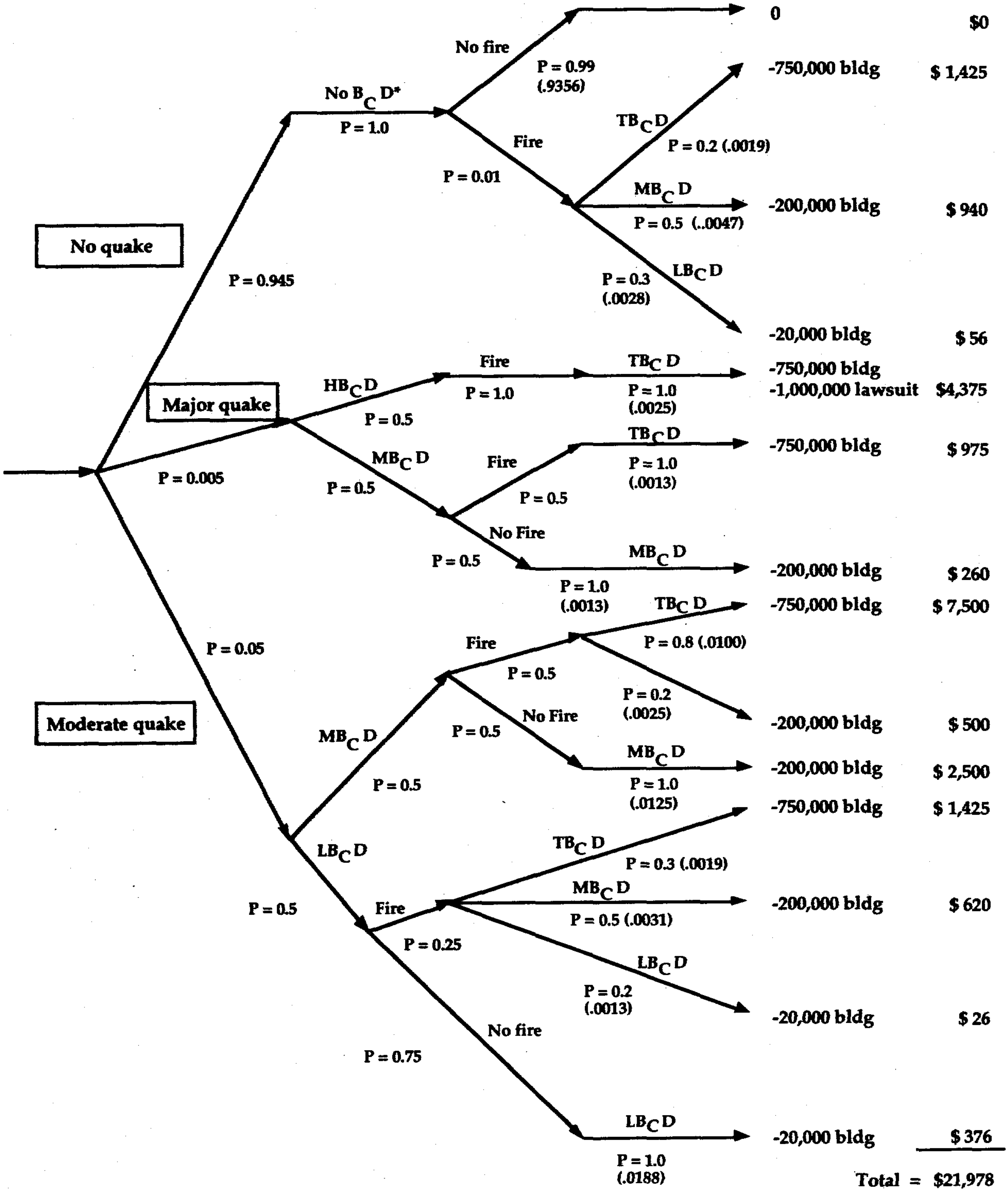
***See Table 12b-3 for damage nomenclature**
Fig. 12b-3. Event tree for Building A — No mitigation.



Expected annual exposure from earthquake and fire = $53,900

***See Table 12b-3 for damage nomenclature**

Fig. 12b-4. Event tree for Building B — No mitigation.



Expected annual exposure from earthquake and fire = \$22,000

***See Table 12b-3 for damage nomenclature**

Fig. 12b-5 . Event tree for Building C — No mitigation.

A second mitigation effort might be the modification of the equipment supports to lower the chance of damage during an earthquake.

Suppose that it is possible to lower the equipment damage level to moderate or light during an earthquake in which a fire does not start or the sprinkler system functions. Assuming that there is a 60% chance of moderate equipment damage during a major earthquake after which the sprinkler system functions, and a 80% chance of moderate damage following a moderate earthquake after which no fire starts or the sprinklers work, the expected annual exposure is reduced to $45,000, or an expected savings of $8,900. If equipment supports can be modified for less than $8,900/year, then this alternative becomes cost effective. It may be, however, that modifications to the equipment supports reduce the functional value of the equipment, rendering this alternative unacceptable, in which case a high-priced insurance premium may be the only acceptable alternative. It is interesting to note that if both the sprinkler-maintenance program and the support-modification program are implemented, the expected annual exposure is $28,800, or an expected savings of $25,100/year, which is greater than the sum of the savings considered independently.

Each of the three building hazard event trees can be used separately in the preceding manner, if each has an annual mitigation budget of its own. However, if mitigation alternatives for the three buildings are in competition for the funding available, then the event trees must be combined into a single event tree that encompasses all possible outcomes for all three buildings on an annual basis. Only in this manner can mitigation alternatives for one building be compared with those for another building, or with composite mitigation efforts for all three buildings.

The preceding examples illustrate both the complexities inherent in earthquake-related risk management problems and the systematic methodology for rationally evaluating and selecting mitigation alternatives that optimize the use of available funds.

Table 12b-3. Damage nomenclature.

Building A	
TB_AC	Total Building A collapse
MB_AD	Moderate Building A damage
TC_AL	Total content loss, Building A
MC_AL	Moderate content loss, Building A
Bldg.	Building
Cont.	Content
Building B	
TB_BC	Total Building B collapse
NoB_BC	No Building B collapse
LB_BD	Light Building B damage
NoB_BD	No Building B damage
S_B Func.	Sprinkler system functions, Building B
SB_B No Func.	Sprinkler system does not function, Building B
SE_BD	Severe equipment damage, Building B
ME_BD	Moderate equipment damage, Building B
LE_BD	Light equipment damage, Building B
Ept.	Equipment
Building C	
TB_CD	Total Building C damage
HB_CD	Heavy Building C damage
MBCD	Moderate Building C damage
LB_CD	Light Building C damage
NoB_CD	No Building C damage

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